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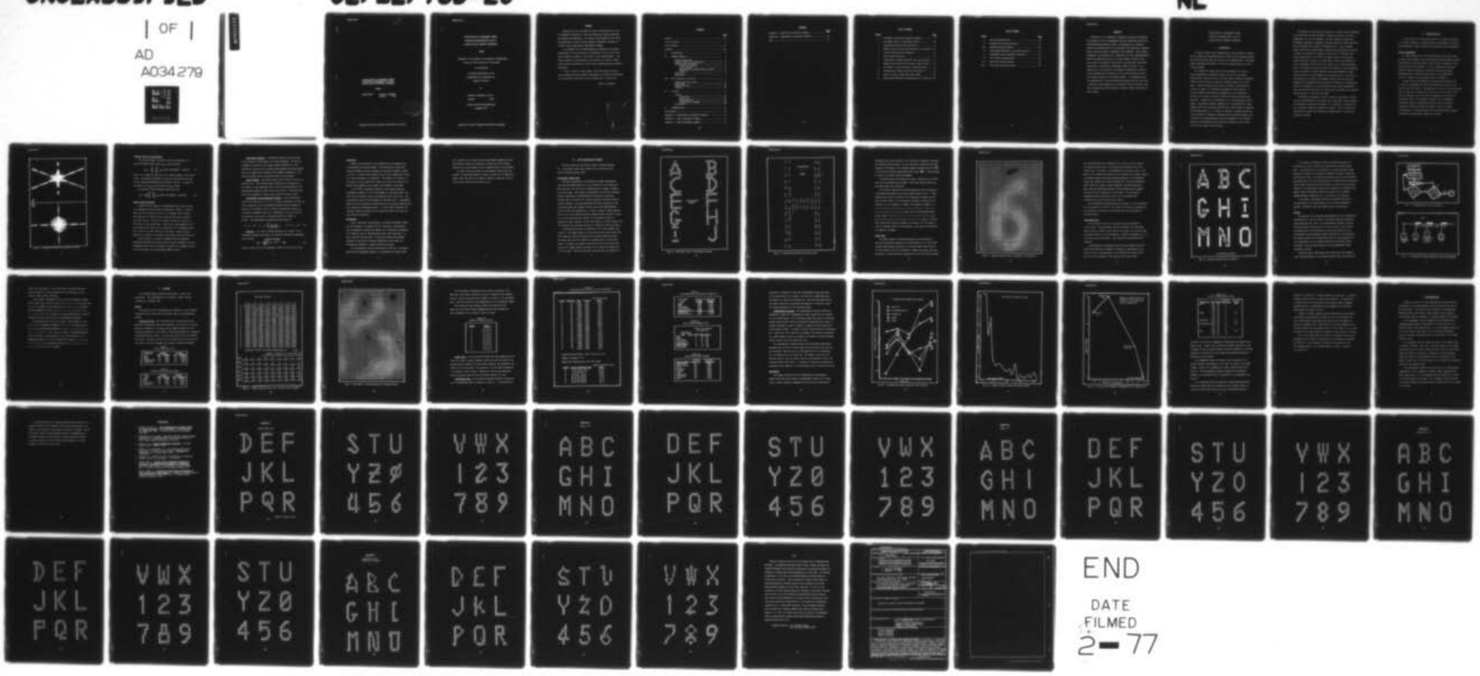

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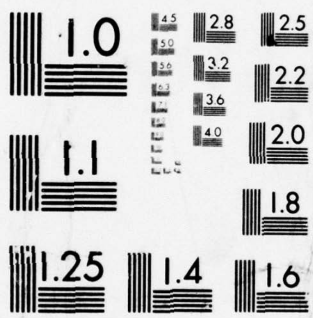

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INVESTIGATION OF ALPHANUMERIC SYMBOL LEGIBILITY DETERMINATION BY USE OF FOURIER SPATIAL FREQUENCY COMPONENTS

THESIS

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Captain USAF

(See form 1473)

GE/EE/76D-20

INVESTIGATION OF ALPHANUMERIC SYMBOL LEGIBILITY DETERMINATION BY USE OF FOURIER SPATIAL FREQUENCY COMPONENTS

THESIS

Presented to the Faculty of the School of Engineering

of the Air Force Institute of Technology

Air University

in Partial Fulfillment of the

Requirements for the Degree of

Master of Science

by

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Graduate Electrical Engineering

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Preface

Legibility is but one aspect of pattern recognition, but it is of fundamental importance. With good legibility, pattern decisions are accurate and efficient. This thesis investigates the use of the two-dimensional, Fourier spatial frequency components to design 36 legible, human recognizable, alphanumeric symbols.

I am indebted to Dr. Matthew Kabrisky, Professor of Electrical Engineering, Air Force Institute of Technology, for his aid and the wide latitude he allowed in the conduct of his investigation. I am deeply grateful to the sponsor of this project, Dr. Larry G. Goble, Flight Dynamics Laboratory, who gave time, understanding and technical assistance.

I wish to thank Dr. Roger Gagnon, Staff Development Engineer, 6570th Aerospace Medical Research Laboratory, for making the facilities of the laboratory available to me and assisting me in their use.

Harvey D. Dahljelm

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Abstract

Legibility is of fundamental importance in pattern recognition. The legibility of five alphanumeric sets was predicted by using the maximum-minimum Euclidean distance of separation in a transform feature space established by the truncated, two-dimensional, discrete Fourier spatial frequency components of the symbols. ASCII, NAMEL, Huddleston, Lincoln/Mitre and a combination set were psychophysically tested and ranked according to the least number of human errors. Test results confirmed the rank order of the legibility prediction: combination, Lincoln/Mitre, Huddleston, NAMEL and ASCII. For a symbol pair, as the distance of separation increased the number of errors decreased and the majority of the errors occurred with the five nearest symbols to the confused symbol. An alphanumeric set was designed with a predicted legibility greater than the test sets. A numeric set was designed with a predicted legibility greater than the Lincoln/Mitre, Mound, Mackworth, Lansdell, NAMEL, Huddleston or ASCII digits.

INVESTIGATION OF ALPHANUMERIC SYMBOL
LEGIBILITY DETERMINATION BY USE OF
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I. Introduction

In order to speed visual communications, each character or symbol must be readily distinguished from all others or else misidentification and confusion might occur and interfere with communication. The visual symbol identification problem is not only a human problem, but also a machine problem.

One concept that might lead to the development of a legible, human recognizable, alphanumeric symbol set for man and machine communication involves the use of Fourier spatial frequency components (FSFC) and the distance of separation between symbols in the FSFC space. Fourier analysis can be used to describe a one-dimensional function in terms of the frequency components of the function. In a similar manner, the frequency components of a two-dimensional function can be found by Fourier analysis and used to describe that function. A symbol can be considered to be a two-dimensional visual image. The spatial frequency components of a two-dimensional visual image can be found by Fourier analysis (Ref 1:20) and used to classify visual images (Ref 1:1). In order to describe a function exactly, an infinite number of frequency components may be required; however, the function can be approximated by using the fundamental low frequency components and deleting the high frequency components that provide only the fine detail of the function.

The purpose of this work was to examine the feature space established by the FSFC basis vectors and design a human recognizable, 36 symbol, alphanumeric set that was legible. In 1975, Vanderkolk, Herman and Hershberger conducted an extensive literature survey of symbol legibility and found legibility in terms of behavioral data: color, contrast, shape, active area, viewing angle, orientation and vibration (Ref 2:80). In light of the ability to classify visual images by FSFC (Ref 1:1), slight manipulations of the FSFC of a symbol should not drastically change the form of a symbol, but might make a symbol more legible and further separated from the rest of the symbols in the human perception space. An extensive historical review and a summary of the mathematical concepts involved in symbol legibility have been published by these authors and only a brief summary will be presented here. The object of this thesis was to design an alphanumeric symbol set using FSFC and maximize the intersymbol minimum distance of separation; to examine the distance of separation of four previously known legible alphanumeric sets, and test the legibility of a constructed set against the predicted legibility order of the four known sets.

The problem is analysed in terms of pattern recognition, discrete Fourier transformations, FSFC feature space operations, legible symbols, and assumptions required for analysis. The symbol data are generated and a resultant symbol set designed and tested. Finally, results and conclusions are given and followed by recommendations to clairfy the legibility problem.

II. Problem Analysis

In this chapter the background material is reviewed in sections on: pattern recognition, discrete Fourier transformations, feature space operations, symbol legibility and problem analysis assumptions.

Pattern Recognition

In 1969, Tallman (Ref 1:36) demonstrated that the inner seven-by-seven (third harmonic) FSFC terms from the two-dimensional Fourier transformation of English symbols could be used to identify (95.8 percent correct) such symbols. In 1973, Ullmann (Ref 3:292-299) described pattern recognition by Fourier optics using Fourier transformations by Fraunhofer diffraction of the alphanumeric symbols A through Z and the numeric digits 0 through 9.

Optical Fourier transformation by Fraunhofer diffraction can be shown in photographs that record the intensity of light in the Fourier plane (Ref 3:296). The intensity at a point in the photographic plane is equal to the square root of the sum of the squares of the real and imaginary part of the Fourier component at the point in the Fourier plane. The alphabetic symbols A and B Fraunhofer diffraction intensity patterns are shown in black in Figure 1, Fraunhofer diffraction intensity patterns, on the next page. By observation of intensity regions the the Fourier plane, pattern recognition of alphanumeric symbols can be made.

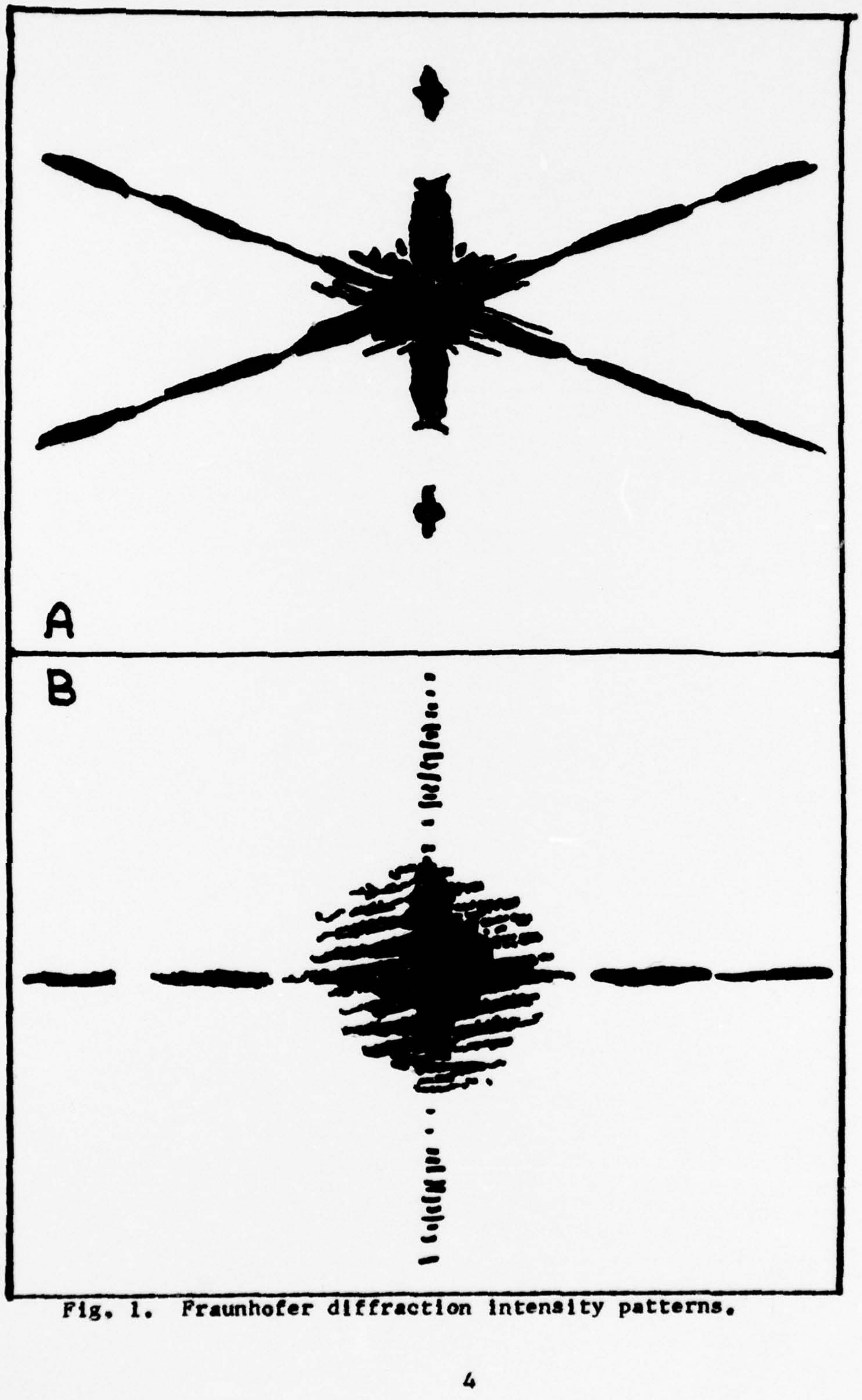

Fig. 1. Fraunhofer diffraction intensity patterns.

Discrete Fourier Transformation

The two-dimensional, discrete Fourier transformation of a M-by-N dimension symbol array, $A_{m,n}$, may be written

$$\alpha_{p,q} = \sum_{n=1}^{N} \sum_{m=1}^{M} A_{m,n} \exp\left\{ -j2\pi \left[(mp/M) + (nq/N) \right] \right\} \tag{1}$$

where p is a modulo-M index and q is a modulo-N index in the Fourier plane. The digital computation is rapidly calculated by the Fast Fourier Transform developed by Cooley-Tukey (Ref 4). A change of one point in the $A_{m,n}$ array changes all $\alpha_{p,q}$ values.

The inverse Fourier transform exists such that

$$A_{m,n} = \frac{1}{MN} \sum_{q=0}^{N-1} \sum_{p=0}^{M-1} \alpha_{p,q} \exp\left\{ +j2\pi \left[(mp/M) + (nq/N) \right] \right\} \tag{2}$$

Feature Space Operations

A symbol feature space is a N-dimensional space that contains the N component feature vectors that describe a symbol. A feature space can be constructed from a set of orthogonal basis vectors. Each FSFC can be a feature vector and each FSFC value a measure along that vector. All FSFC of a symbol indicate the location of the symbol in the feature space. Each symbol, approximated by its low-frequency FSFC terms, can be represented by a N dimension vector and it will lie at some location in the space. Several similar symbols will cluster in the region of the symbol they are similar to.

In such a space, a variety of operations may be performed: statistical measures can be made on the N vector components, linearly independent vector sets may be used to construct an orthogonal vector set, and distances can be determined between vectors.

Statistical Measures. A statistical measure can be the mean or the variance of some values of a vector component. The mean of N samples is the sum of the N sample values divided by N. The variance is the sum of the N sample values squared minus the squared sum of the sample values divided by the number of samples, N. The mean-to-variance ratio is the mean divided by the variance.

Scalar Product. The scalar product of two vectors, x and y, is denoted $\langle x,y \rangle$. The scalar product operation is the summation of the product of each component value in the vector multiplied by the corresponding component value in the other vector. Two vectors are said to be orthogonal if their scalar product is equal to zero.

Gram-Schmidt Orthogonalization Process. In an N-dimensional space, for M less than N, a set of M linearly independent vectors, x_m, can be processed by the Gram-Schmidt orthogonalization process to construct an orthogonal set of M linearly independent vectors, y_m, A linearly independent vector of N components, is a vector that is not the sum of the product of constants thimes the other M-1 vectors. The Gram-Schmidt orthogonalization process is

$$y_1 = x_1 \quad \text{and} \quad y_j = x_j - \sum_{i=1}^{j-1} \frac{\langle y_i, x_j \rangle}{\langle y_i, y_i \rangle} y_i \qquad j = 2, 3, \ldots, M \tag{3}$$

Distance. It is easy to define "distance" in a space. In an orthogonal, N-dimensional space, the Euclidean distance of separation may be written

$$d_{\alpha\beta} = \sqrt{\sum_{i=1}^{N} (\alpha_i - \beta_i)^2} = d_{\beta\alpha} \tag{4}$$

where α_i and β_i are the i-th component values of the vector α and β.

Legibility

Symbol pair legibility is the capability of one symbol being distinguished from another symbol. Using distance of separation, identical symbols have zero distance of separation because α equals β in Eq 4. A slight form variation from the first symbol will result in a non-zero distance of separation. The smaller the distance in the space, the more similar the symbol; the larger the distance, the greater the legibility of one symbol with respect to the other.

In the 1950's, legibility research on the optimal design of alphanumeric symbols led to the development of the NAMEL symbol (Ref 2:81) and the Lansdell, Mound, and Mackworth digits (Ref 5:78). The Lincoln/Mitre symbols were developed in 1966 (Ref 2:85). Alphanumeric symbol sets were developed by Huddleston and the American Standard Code for Information Interchange (ASCII). In 1975, Kabler digitized 150 different legible alphabets of 26 letters each (Ref 6), but did not study them for legibility.

Assumptions

ASCII, Huddleston, Lincoln/Mitre, and NAMEL alphanumeric symbol set were assumed to be legible and the continuous two-dimensional solid alphanumeric symbols were assumed to be adequately represented by a discrete, binary, two-dimensional array with dimensions: 42 units high and 30 units wide. To avoid the aliasing and leakage problems of the Fourier transform computation, each symbol was centered and imbeded in a zeroed 64-by-64 unit array.

The low-frequency, inner seven-by-seven, FSFC (Eq 1) adequately describe the alphanumeric symbol in a 49-dimensional feature space

and a symbol can be constructed from the Fourier components (Eq 2). Two different symbols are separated in FSFC space and Euclidean distance (Eq 4) was assumed to be an adequate metric for legibility.

The size, height and width, of the designed symbols were not allowed to change from symbol to symbol or symbol set to symbol set. Symbol lines also were not allowed to change in intensity, nor the two unit line width by more than one unit.

III. Data Generation and Testing

The data generation and testing chapter includes sections on: flying-spot scanner data, Kabler data, constructed data, and the testing procedure used.

Flying-spot Scanner Data

The ASCII, Huddleston, Lincoln/Mitre and NAMEL alphanumeric sets had each symbol drawn on a 14 unit high by 10 unit wide grid. Each unit was a dot and the dot representation is shown in Figure 2 on the next page. Each symbol was digitized by the 6570th Aerospace Research Laboratory's System Research Laboratories Flying-spot scanner under the control of a Digital Equipment Corporation PDP-12 digital computer. The two-dimensional FSFC were calculated on the Wright-Patterson AFB, Computer Center Control Data 6600 computer. The FSFC terms were computed by Dr. Roger A. Gagnon's PREVIP program (Ref 7); the unit energy normalized components were low-pass filtered to the inner seven-by-seven terms; the intersymbol distance of separation matrix computed, and for each symbol, the other symbols were rank ordered with increasing distance of separation from that symbol.

The digitized data was not identical to the input symbols, see Figure 3. The ragged edges of the circular dots and stray noise dots were removed by manual intervention and internal areas with holes were made solid with the addition of missing units in the 64-by-64 array. Of course, the change of even one unit of the 64-by-64 unit array of the symbol alters the energy in the symbol and changes all the FSFC terms. The FSFC terms were calculated and the distance of

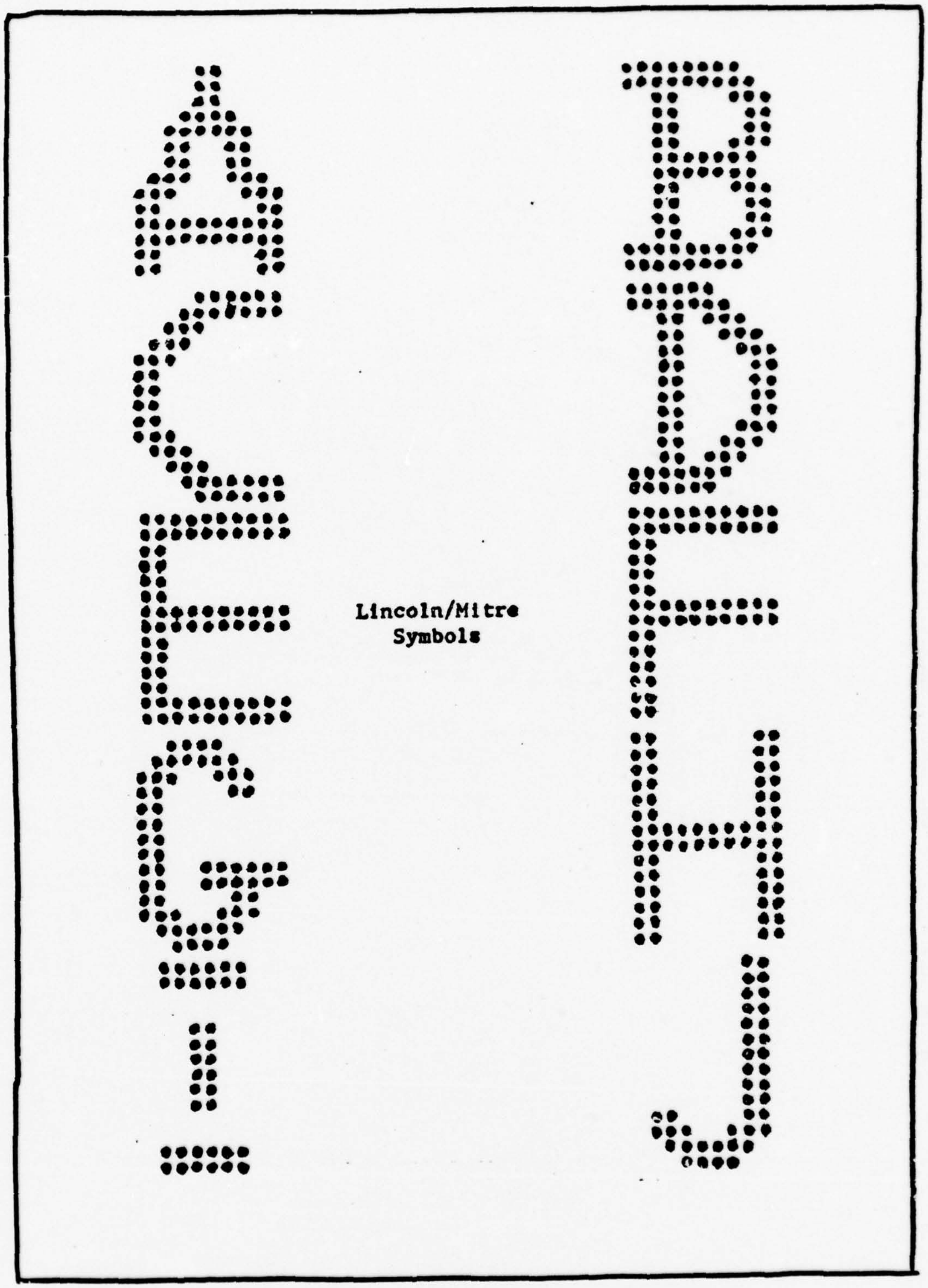

Fig. 2. Dot symbol input to Flying-spot scanner.

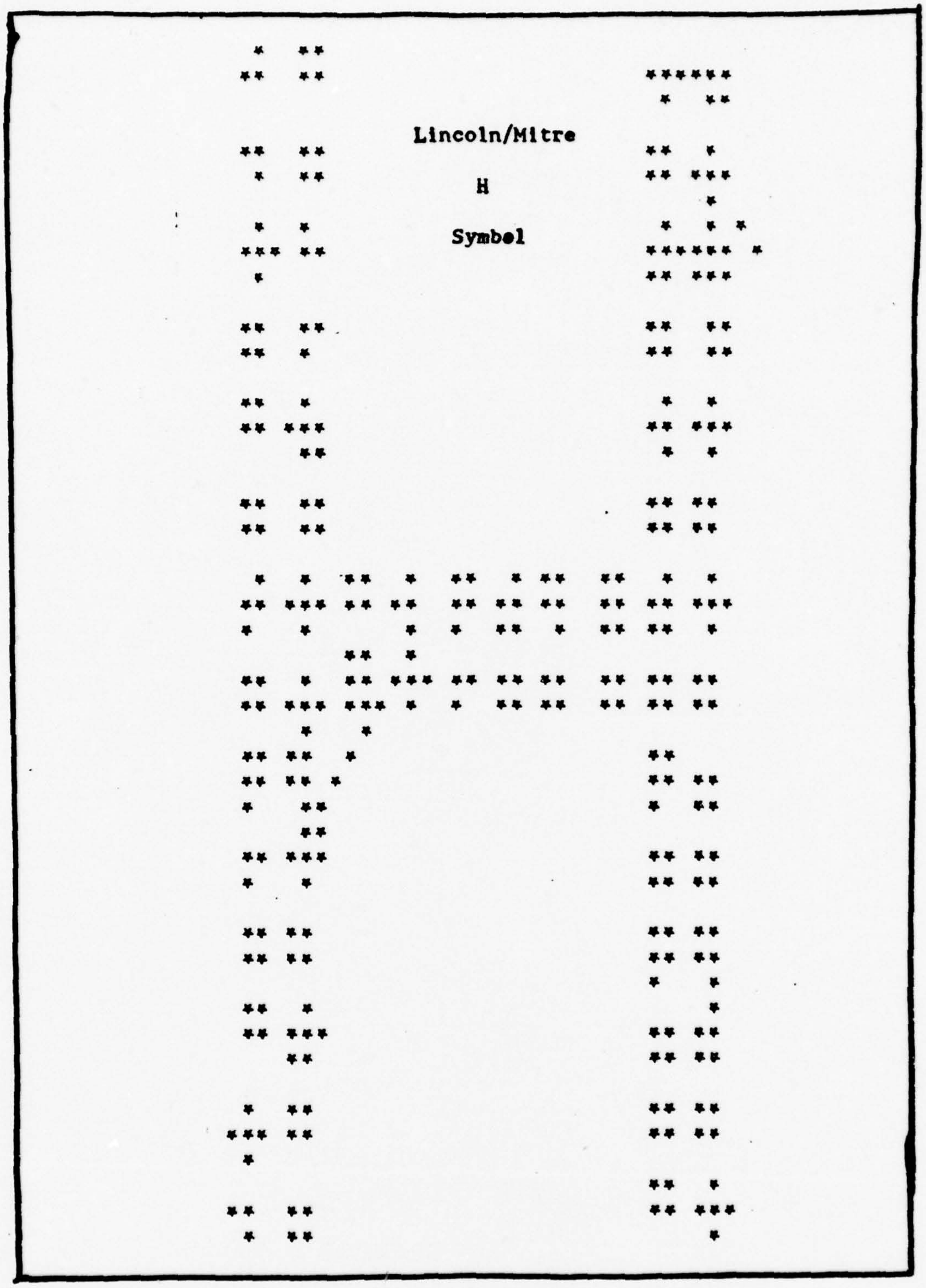

Fig. 3. Flying-spot digitized data with noise.

separation matrix was computed. The distances of separation increases and decreases were recorded. Not all holes were filled and dots were enlarged or decreased; with developed symbols resembling Braille () or the American Banking Association check digits (). The direction of change of the FSFC terms was recorded.

Six modification calculations were made. Statistics on the FSFC terms for each symbol were recorded. The scalar product matrix for all symbol pairs was calculated.

The 36-by-36 symbol scalar product matrix was used to construct a Gram-Schmidt orthogonal set of new symbol vectors by Eq 3. Three sequences were used to construct the orthogonal new symbol vectors from the FSFC terms: L) the sequential sequence A through Z and 0 through 9; 2) the frequency of usage in the English language E, 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, T, R, I, N, O, A, S, D, L, C, H, F, U, P, M, Y, G, W, V, B, X, K, Q, J and Z, and 3) the smallest scalar product pairs: Z, 6, H, I, 1, T, 0, O, L, J, C, E, G, W, 2, 5, S, B, D, A, M, N, Q, 8, U, 7, F, K, 3, V, X, Y, 4, R, P and 9. The new FSFC symbols were printed by PREVIP, see Figure 4 for the symbol 6 that was produced from the third sequence. The amount and direction of change was recorded.

Kabler Data

The small number of flying-spot samples was insufficient to calculate statistical measures on the FSFC terms, but in 1975 Kabler produced 3900 symbols digitized in a 32-by-32 array format (Ref 6). The 150 different sets of 26 alphabetic symbols flying-spot data was processed by a modified PREVIP program and the 49 FSFC terms recorded.

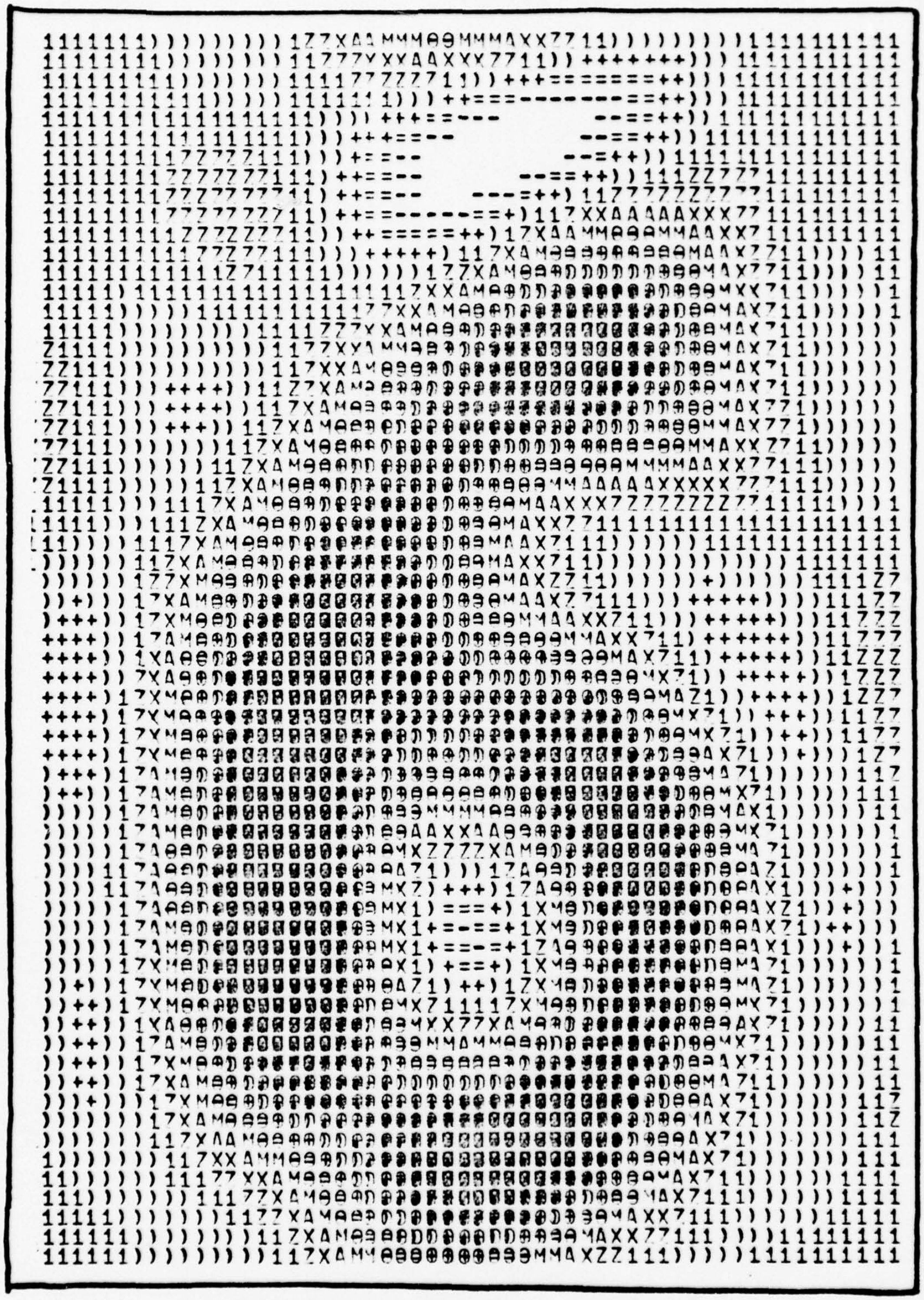

Fig. 4. PREVIPS Inverse Fourier Transform of the digit 6.

The modification was the increasing of the width of narrow symbols; the height-to-width ratio of each symbol was reduced to less than three-to-one. The symbol I was normalized to six-to-one ratio. The height of the symbols was constant, but the width of the symbol varied. The height-to-width ratio was normalized because a unit rectangular signal has a smaller, but wider spectrum than a two unit rectangular signal that has a larger, narrow transform. The FSFC population mean, variance and mean-to-variance ratio statistics were computed for each of the 49 components of each symbol. The statistical computations were recalculated after the 49 components were normalized by the first (DC) harmonic term.

The Fraunhofer diffraction patterns of Figure 1 can be determined from the squares of the FSFC. The Kabler FSFC terms were squared and the statistics calculated on the squared data and the squared DC normalized data.

Constructed Data

The flying-spot data was constructed using non-connective circular dots. The constructed data was developed with connecting square units to produce a solid figure, see Figure 5 on the next page for sample letters of the Lincoln/Mitre symbols and Appendix A, B, C, D and E for the other symbols. The flying-spot computations were repeated.

An experimental alphanumeric symbol set was designed using the Kabler data statistical component information, observations of the inverse Fourier transformations of the modified flying-spot FSFC, and unit block movements in the 14-by-10 unit symbol array.

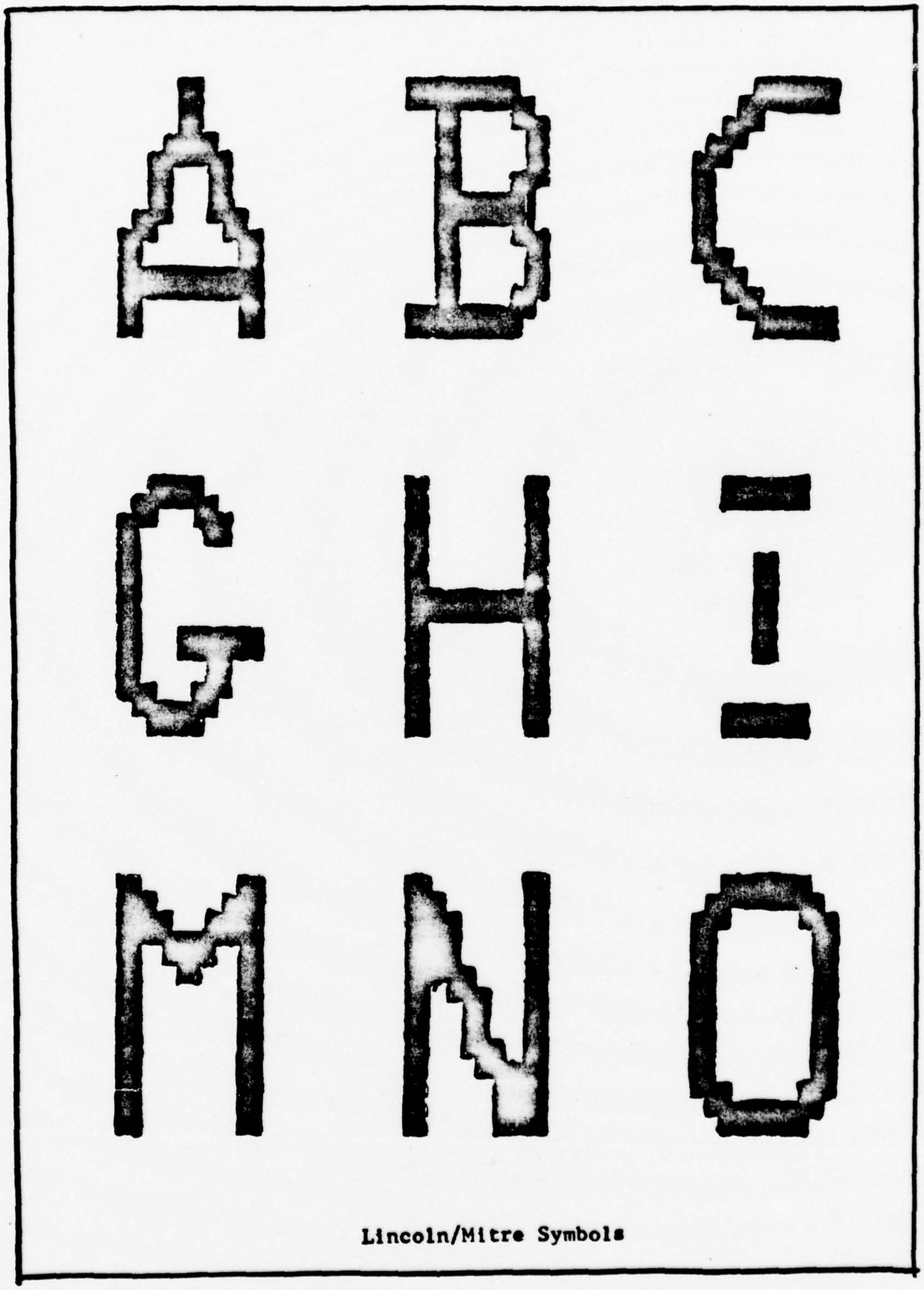

Fig. 5. Digital Constructed Data Examples

A 144 symbol, intersymbol distance of separation matrix was calculated for ASCII, Huddleston, Lincoln/Mitre and NAMEL symbol sets. A combination set was developed by a manual iterative search procedure to maximize the minimum intersymbol distance of separation over the entire set. The iterative procedure was, a set was selected, the symbol pair with the minimum distance of separation was determined, either symbol was substituted to develop a new set and the procedure repeated. The experimental symbols were added and the resultant 180 symbol, 180-by-180 distance matrix was searched for a maximum-minimum distance combination set. See Figure 6 for procedure.

A 144 symbol, intersymbol distance of separation matrix for the experimental set; Lincoln/Mitre set; the ASCII, Huddleston, Lansdell, Mackworth, Mound and NAMEL digits, was calculated.

Testing

The testing of the generated alphanumeric sets was independently conducted by Dr. Larry G. Goble of the Flight Dynamics Laboratory, Wright-Patterson AFB, Ohio. The psychological legibility testing had the observer subject fixate on a dot; a mask of a dot pattern was exibited for 15 milliseconds; the mask was removed for five milliseconds; the alphanumeric symbol exibited for 15 milliseconds; the symbol removed for 5 milliseconds; the dot mask displayed for 15 milliseconds, and the subject identified the observed symbol. See Figure 7 for the time sequence of the psychophysical human perception testing.

Over five days, 9,000 symbols were observed by five subjects and a confusion matrix of the exibited symbol versus the identified

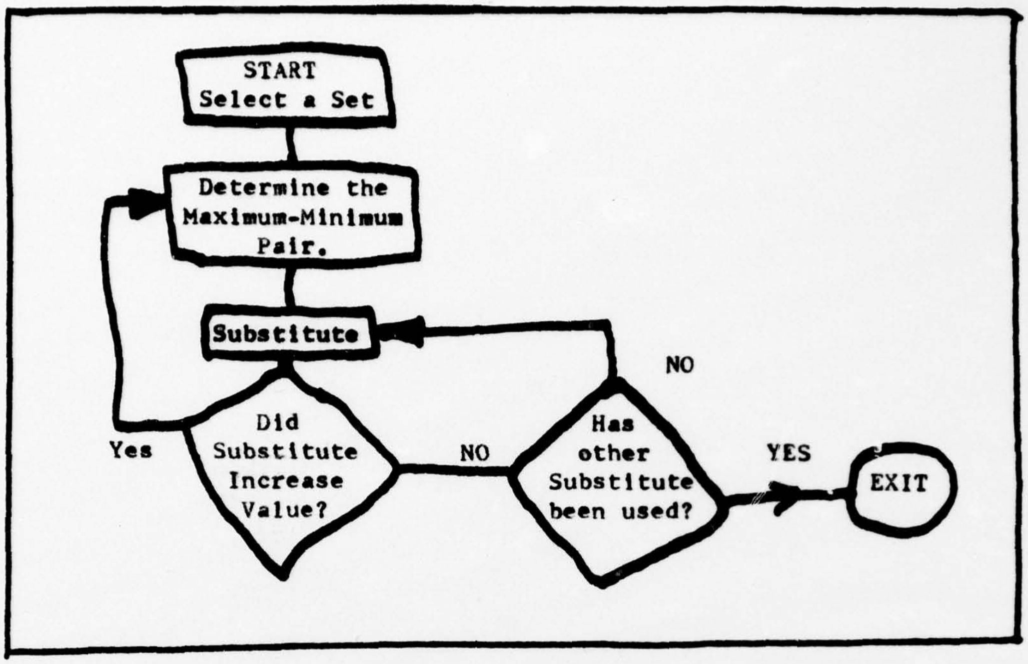

Fig. 6. Maximum-minimum search procedure.

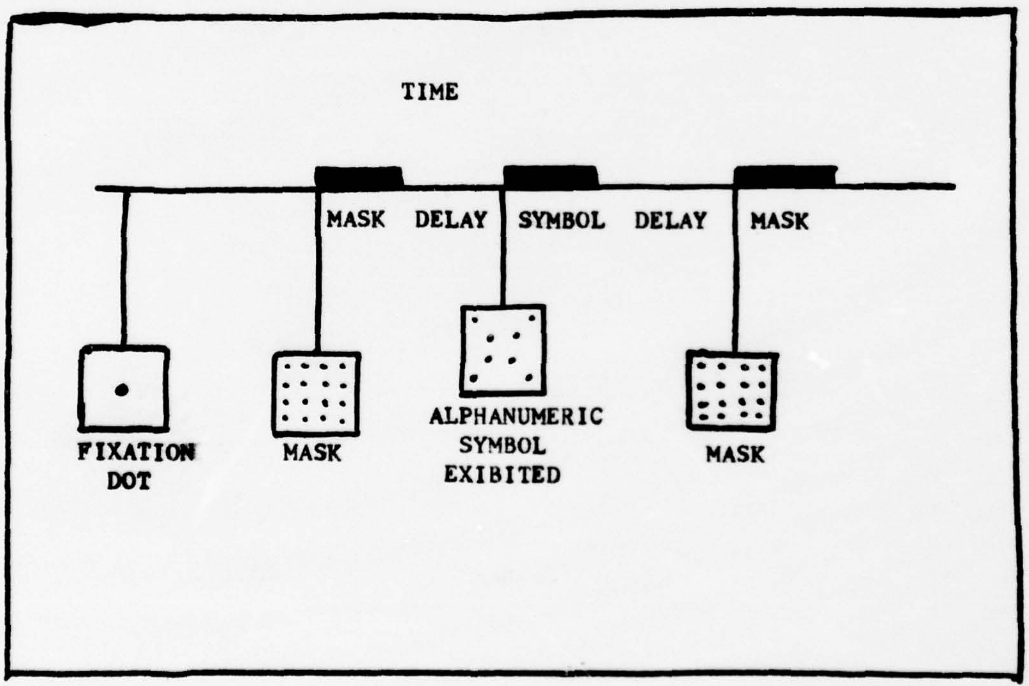

Fig. 7. Psychophysical Human Recognition Test Time Sequence.

symbol was constructed. On the third day, the symbol exibition time was reduced to 10 milliseconds to avoid saturation at 100 percent correct symbol selection.

The 36 symbol alphanumeric sets of ASCII, Huddleston, Lincoln/Mitre, NAMEL, and a test set of the F, M, R, T, U, 2 of the ASCII set; the C, E, K symbols of the NAMEL set; the B, N, P, S, W, 8 symbols of the Huddleston set; the A, D, G, H, I, J, L, O, Q, V, X, Y, Z, 0, 1, 3, 4, 5, 6, 7 and 9 symbols of the Lincoln/Mitre set, were the symbols of the test set used in the psychophysical testing.

The combination set of the four sets: ASCII symbols A, F, M, R, T, U, Z, 2; Huddleston symbols B, N, P, S, W, 8; NAMEL symbols C, E, K; and Lincoln/Mitre symbols A, D, G, H, I, J, L, O, Q, V, X, Y, 0, 1, 3, 4, 5, 6, 7 and 9, was not tested. The combination set of the five sets: ASCII symbols H, L, M; NAMEL symbols C, K, 5; Huddleston symbols B, N, S, W; Lincoln/Mitre symbols A, D, J, O, Q, V, Y, Z, 0, 3, 7, 9; experimental symbols E, F, G, I, P, R, T, U, X, 1, 2, 4, 6 and 8, was not tested.

IV. Findings

The findings chapter includes two sections: results and conclusions. The investigation was initiated 1 August 1976 and concluded on 1 November 1976.

Results

The results of this investigation are reported in four sections: flying-spot data, Kabler data, constructed data, and psychophysical testing.

Flying-spot Data. The flying-spot data 49 FSFC terms and the distance of separation matrix were computed. See Figure 8 on the next page for an example of a distance matrix computer printout and the increasing ordering for each symbol. The minimum distance of separation is presented below in table I for noisy data and Table II for reduced noise data. The ASCII C-G pair was the minimum pair for both runs and the NAMEL H-1 pair the maximum, even though the distances changed.

Table I
Noisy Flying-spot Data.

Symbol Set	Minimum		Maximum	
	Pair	Distance	Pair	Distance
NAMEL	C-G	.2401	H-I	1.0920
ASCII	C-G	.2336	F-J	1.0640
Lincoln/Mitre	P-R	.3304	H-1	.9412
Huddleston	I-1	.3242	L-7	.9483

Table II
Reduced Noise Flying-spot Data.

Symbol Set	Minimum		Maximum	
	Pair	Distance	Pair	Distance
NAMEL	C-G	.2404	H-1	1.1370
ASCII	C-G	.2352	F-J	1.0640
Lincoln/Mitre	K-X	.2956	H-1	.9905
Huddleston	I-1	.3206	U-1	.9656

DISTANCE MATRIX

	A	B	C	D	E	F	G	H
A	0.0000	.5321	.6356	.5107	.5843	.6116	.5232	.6310
B	.5321	0.0000	.6485	.3112	.3906	.5513	.4793	.6121
C	.6356	.6485	0.0000	.6432	.4602	.6567	.5011	.7464
D	.5107	.3112	.6432	0.0000	.4695	.5545	.4466	.6611
E	.5843	.3906	.4602	.4695	0.0000	.4748	.4814	.6314
F	.6115	.5513	.6567	.5545	.4748	0.0000	.4980	.4900
G	.5232	.4793	.5011	.4466	.4814	.4980	0.0000	.6519
H	.6310	.6121	.7464	.6611	.6314	.4900	.6519	0.0000
I	.6808	.5391	.6398	.5639	.5007	.7439	.6194	.8035
J	.7360	.5704	.8120	.6424	.7055	.9025	.7048	.7583
K	.5172	.5441	.5986	.5771	.4955	.4782	.5313	.5080
L	.8867	.7783	.6857	.7242	.6847	.7195	.7257	.6489
M	.5751	.5423	.6863	.5135	.5127	.5968	.6731	.6095
N	.6131	.5393	.6415	.5799	.5812	.5832	.5613	.4048
O	.5944	.5053	.4518	.5014	.4561	.6063	.4252	.5996
P	.6660	.5897	.7324	.6067	.5666	.2985	.6190	.4570
Q	.5117	.5062	.5992	.5990	.5278	.5540	.4962	.5490
R	.5818	.5106	.6236	.5586	.5368	.4204	.5219	.4495
S	.4860	.4515	.5676	.5017	.5058	.6306	.3747	.6880
T	.6839	.5988	.6440	.6246	.5340	.6949	.6013	.9092
U	.7126	.5850	.6079	.5837	.5134	.7078	.6402	.6238
V	.6877	.5130	.6697	.5372	.5772	.6304	.5323	.5425
W	.5112	.4344	.5787	.4921	.4375	.4856	.4702	.5402

DISTANCE MATRIX HAS BEEN NORMALIZED BY .7402

ORDERED DISTANCE TO EACH PROTOTYP

SYMB	A	4	S	8	D	W	Q	K	6
A	0.0000	.4441	.4860	.5021	.5107	.5112	.5117	.5172	.5199
SYMB	B	D	2	Z	E	8	W	S	3
B	0.0000	.3112	.3490	.3851	.3906	.4179	.4344	.4515	.451[illegible]
SYMB	C	O	E	4	G	5	8	S	W
C	0.0000	.4518	.4602	.4938	.5011	.5420	.5593	.5676	.5787
SYMB	D	B	8	G	2	E	W	O	S
D	0.0000	.3112	.4342	.4466	.4473	.4695	.4921	.5014	.5017
SYMB	E	B	8	Z	W	O	C	D	5
E	0.0000	.3906	.4229	.4344	.4375	.4561	.4602	.4695	.4725
SYMB	F	P	R	5	3	E	K	W	H
F	0.0000	.2985	.4204	.4486	.4553	.4748	.4782	.4856	.4900

Fig. 8. Example Distance Matrix and Nearest Symbol Ranking.

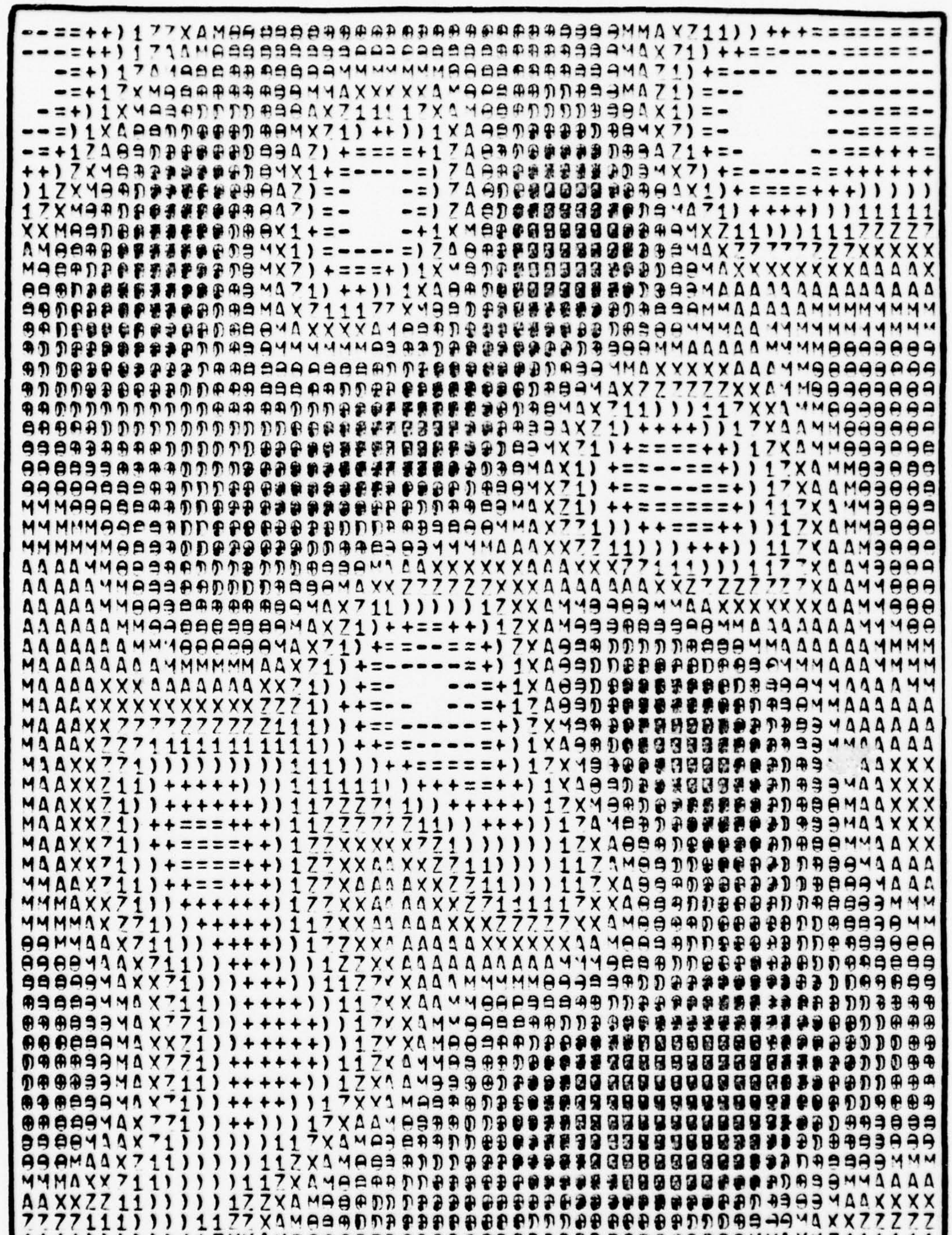

Fig. 9. New Symbol 6 from Gram-Schmidt Orthogonalization.

The Gram-Schmidt orthogonalization process was applied to the FSFC data, the inverse transform in Figure 4 represents data symbol 6. Figure 9, the new orthogonal-to-Z, symbol 6 is shown on the preceeding page. The third symbol was not recognizable as an alphanumeric symbol.

The flying spot data distance matrix was ordered for each symbol and the symbol closest neighbor families was observed for each alphanumeric set as shown in Table III below.

Table III
Huddleston Symbol Families

Symbol	Family
C	O Q E S 8
D	B Q O S O
F	P E K R A
I	T 1 3 7 B
O	C G Q O 5
P	M F E O R
Q	O G A O C
X	K W N M S
0	O B 2 8 Q
2	Z B E R 8
6	8 B O E S
7	9 Z Y 2 I
8	O 6 9 A Q

Kabler Data. The size-modified Kabler data was normalized by the first (DC) term to observe component ratios and the rank order of the largest mean-to-variance for each symbol component was determined, see Table IV on the next page. The statistics for the symbol components is included in Table IV also. Squaring the raw data increased the mean-to-variance ratio, but the rank order remained the same.

Constructed Data. The minimum and maximum distance of separation for the constructed data is presented in Table V. A distribution of

Table IV
Kabler Data Normalized By DC term Statistics

Symbol	Component	Mean	Variance	Mean-to-Variance Ratio
A	9	-.4561	.0195	-23.4
B	10	-.3194	.0128	-24.9
C	21	.6422	.0487	13.2
D	17	.3482	.0223	15.6
E	16	.2011	.0149	23.1
F	29	-.1404	.0176	-25.6
G	23	-.5201	.0313	-16.6
H	31	.2340	.0109	21.5
I	24	-.2052	.0029	-70.3
J	23	-.3251	.0086	-37.9
K	10	-.4413	.0152	-29.1
L	24	.3771	.0149	-25.3
M	9	-.4088	.0243	-16.8
N	23	-.2296	.0080	-28.6
O	42	.2708	.0244	11.1
P	21	.2504	.0086	29.2
Q	37	-.1333	.0152	- 8.7
R	10	-.3616	.0134	-26.9
S	10	-.4075	.0174	23.4
T	13	.2636	.0115	27.8
U	24	.2978	.0229	-13.0
V	23	-.1462	.0064	23.0
W	10	-.4928	.0333	-14.8
X	21	.4453	.0236	18.8
Y	10	-.4531	.0221	-20.5
Z	9	-.4126	.0324	-12.7

Mean-to-Variance Ratio: High = 70.3, Low = 0.1

Number of Samples = 113

Kabler Data Normalized by first (DC) term.

Symbol	Largest Component Order	Mean-to-Variance Ratio Range
E	16 15 11 23 9 21 10	23-13
F	9 29 23 21 4 16	27-13
P	9 21 24 29 47 8	33-15
B	10 23 24 9 42 21	27-18
C	24 23 25 21 11 41	17-12
Q	24 13 14 21 23 25	9- 6
O	42 41 23 24 47 22	11- 7
U	24 23 31 17 18 37	13- 8

Table V
Constructed Data Distances of Separation

Type Symbol Set	Distance of Separation Minimum	Maximum
ASCII	.2022	1.5605
NAMEL	.2022	1.5512
Huddleston	.4116	1.5527
Lincoln/Mitre	.4328	1.5752
Combination of 4	.4694	1.5752
Experimental	.4032	1.5092
Combination of 5	.5616	1.5729

Table VI
Set Distance Histogram Data

Symbol Set \ Range Bin	.25	.50	.75
	Number of Distances in Range Bin		
ASCII	4	52	254
NAMEL	2	30	174
Huddleston	0	16	210
Lincoln/Mitre	0	14	188
Combination	0	6	144
Experimental	0	10	156
Combination	0	0	98

Table VII
Digit Set Minimum Distances

Type of Digits	Minimum Digit Pair	Distance of Separation
Experimental	3-5	.6390
Lincoln/Mitre	2-8	.6255
Mound	3-8	.6271
Mackworth	3-5	.6102
Lansdell	3-8	.6042
NAMEL	5-6	.5983
Combination	5-0	.5734
Huddleston	6-8	.4512
ASCII	0-8	.3016

distances is presented in Table and the predicted legibility order of the tested sets is as follows: the test set, Lincoln/Mitre set, Huddleston set, ASCII set and NAMEL set. The predicted legibility of the numeric digits was calculated and presented in Table VII, Digit Set Minimum Distances, on the preceeding page.

Psychophysical Testing. The psychophysical testing results are presented in Figure 10, Psychophysical Symbol Legibility Test Results, on the following page. On the following pages, the number of incorrect identification errors versus the distance of separation rank order of closest neighbors is shown in Figure 11, Number of Errors versus Rank Order-Distance Number. In Figure 12 Errors versus Distance of Separation for a Symbol Pair, the results of increasing the distance of separation on a given symbol, C and G, are shown as the number of errors decrease. Similar results occur for symbol pair O-Q.

The non-symmetric confusion matrix was constructed from subject responses and the order of least number of errors after the fifth day was predicted: the test set, the Lincoln/Mitre set, the Huddleston set, the NAMEL set and the ASCII set. The number of errors in the confusion matrix that are greater than ten are presented in Table VII, Confusion Matrix Error Pairs. An analysis of variance calculation was performed, which produced a .01 significance level for the test results.

Conclusions

The primary objective of the investigation of alphanumeric symbol legibility was to design an alphanumeric symbol set by using Fourier spatial frequency components and test that set against the

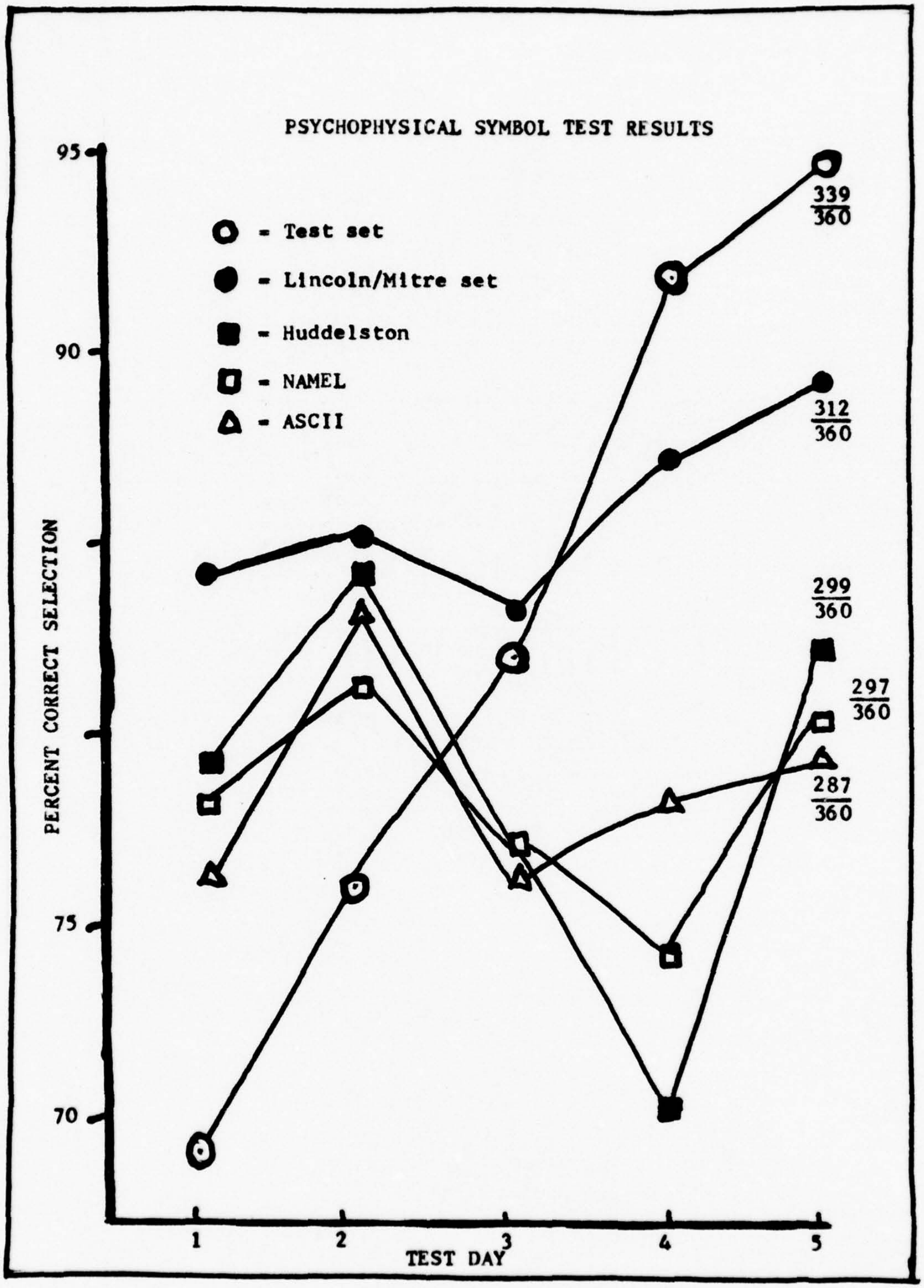

Fig. 10. Psychophysical Symbol Legibility Test Results.

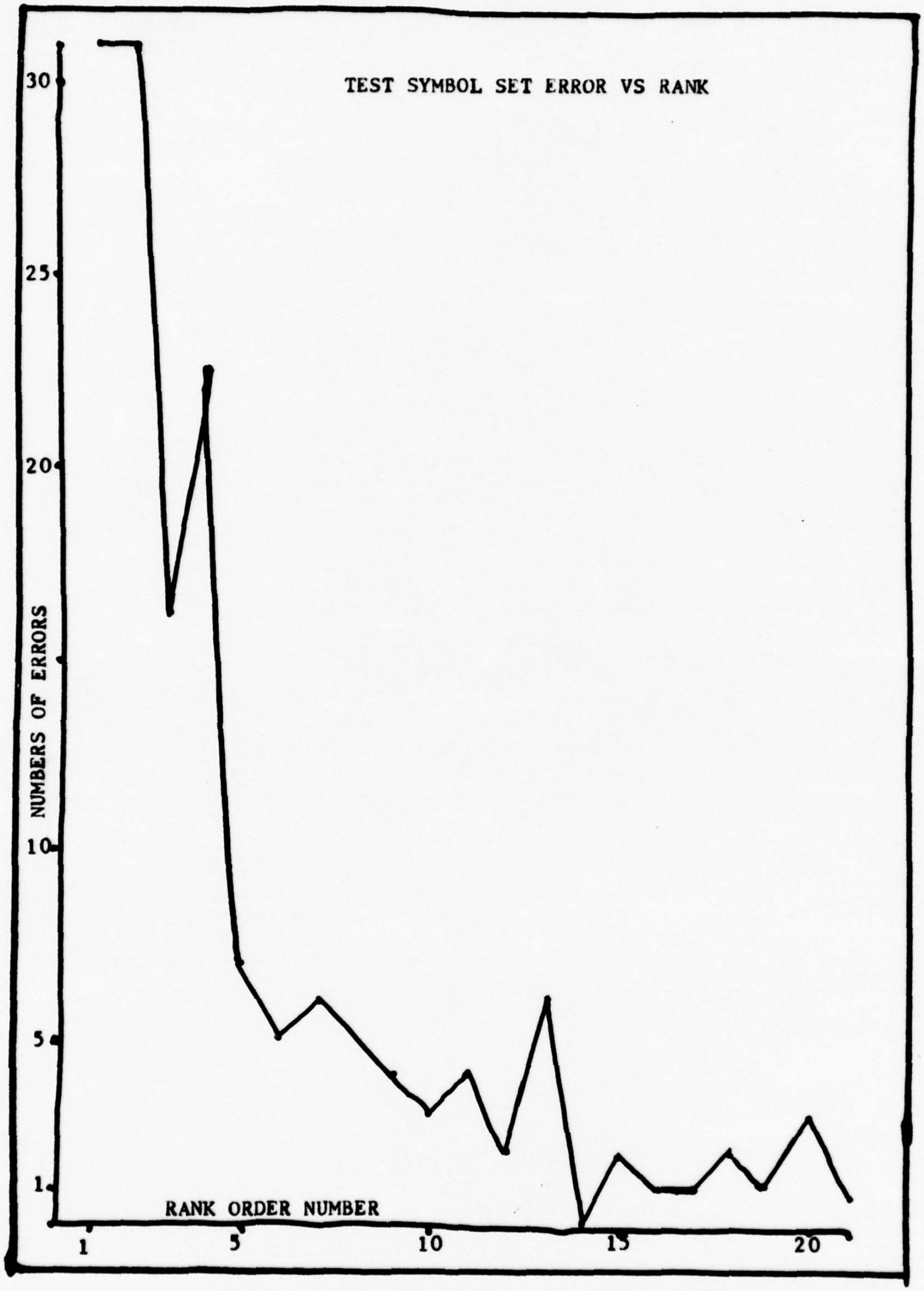

Fig. 11. Number of Errors versus Rank Order Number

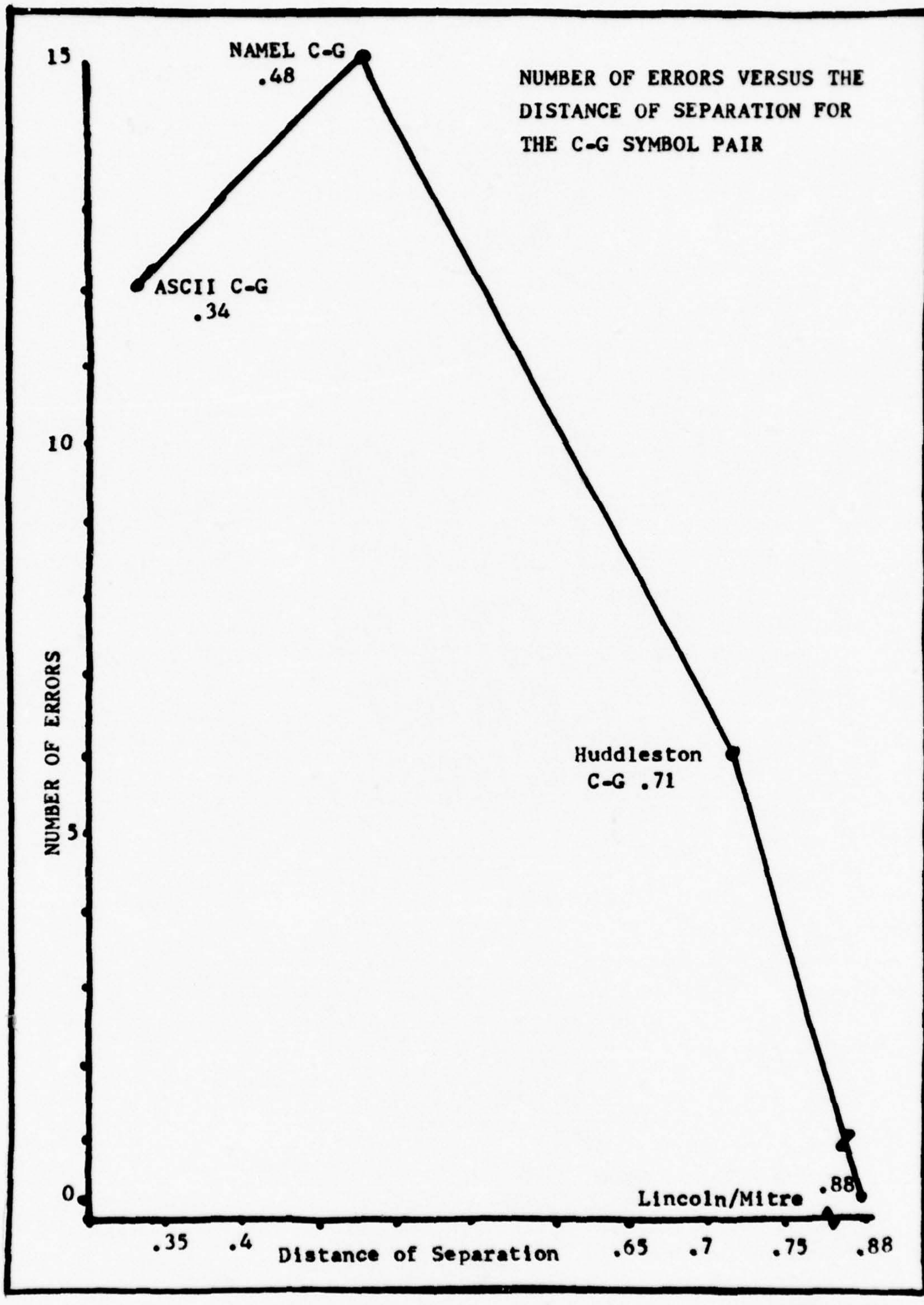

Fig. 12. Errors versus Distance of Separation for a Symbol Pair.

Table VIII
Confusion Matrix Error Pairs.

Symbol Set	Pair	Errors	Distance Rank Order	Set Total Errors
ASCII	C-G	12	1	392
	I-1	12	1	
	P-R	13	2	
	S-8	10	1	
	3-8	12	2	
NAMEL	I-1	36	2	404
	O-0	19	2	
	V-X	16	4	
	C-G	15	1	
Huddleston	G-6	18	1	379
	P-R	18	3	
Lincoln/Mitre	2-9	19	4	259
	T-8	13	13	
	I-1	12	2	
	P-R	12	1	
Test	S-8	14	6	279
	1-9	12	3	
	P-R	10	3	

legibility of the ASCII, Huddleston, Lincoln/Mitre and NAMEL alphanumeric sets. To meet this objective and predict legibility it was necessary to find the Fourier spatial frequency components of several alphabetic and numeric sets and compute the Euclidean distance of separation in FSFC space.

The assumptions stated in Chapter II were justified by the inverse Fourier transformation of the FSFC, see Figure 4, and small changes in some of the components of widely varying symbols, see Table IV. The Gram-Schmidt process can generate new separated symbols, but the symbols are not recognizable as alphanumeric, see Figure 9.

It is concluded that the objective of this investigation was obtained by using the first, second and third harmonic terms as a basis for a FSFC feature space, and use of maximized Euclidean

distance of separation to increase symbol pair legibility. Euclidean distance in FSFC space is a metric for legibility. The legibility of symbol sets can be predicted by rank ordering them by maximum-minimum distance of separation and the histogram of the distance distribution, see Table V and VI.

Families of similar symbols can be constructed by rank ordering the distance of separation, see Table III, and the FSFC terms of a family have similar large mean-to-variance ratios for samples of different alphabetic sets. From Table IV, the tenth component has a mean-to-variance ratio of greater than 25 for the family B, R, K, and Y. The value of the tenth component increases in value across the family.

For a given symbol pair, the number of recognition errors can be decreased as the distance of separation of the symbols is increased, see Figure 12. The recognition errors are the largest with the five closest symbols to a confused symbol, as shown in Figure 11 and Table VIII.

V. Recommendations

Although the results of this investigation are statistically significant, in the testing phase only five subjects were used in the 9,000 tests. The rising curves in Figure 10, Psychophysical Symbol Legibility Test Results, might level off and converge as the observers learn the symbols, as increased symbols are observed.

It is recommended that the combination set designed with a maximum-minimum distance of separation of .5616 be tested by ten observers using 18,000 observations. It is also suggested that the first 9,000 tests be made using a five millisecond observation time and the final 9,000 tests using 15 milliseconds as the symbol exibition time.

It is suggested that the height and width of the symbol should be allowed to change. Since even a one point change in the digital representation of the symbol changes the FSFC terms, the line width should be allowed to change and a variation in the digitization resolution should be investigated to find the boundaries of the region a symbol lies in the FSFC space, but the symbol line intensity should not be allowed to vary.

This investigation prediced the legibility of the experimental, Lincoln/Mitre, Mound, Mackworth, Lansdell, NAMEL, Huddleston and ASCII numeric sets. It is recommended that the legibility of these sets be psychophysically tested. It is suggested that the Braille and American Banking Association magnetic checking digits be included in the study.

The investigation used a square, seven-by-seven, filter; it is suggested that the first harmonic term be not used because it is a measure of the number of units used to construct the symbol. Use of the second, third and fourth harmonic terms is recommended and a rectangular filter be constructed to contain horizontal terms in a greater proportion to the vertical terms because of the width changes in a symbol from set to set.

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Appendix A

Lincoln/Mitre Set

(Fig 5 is also in set)

S T U

Y Z Ø

4 5 6

V W X

1 2 3

7 8 9

Appendix B

ASCII Set

A B C

G H I

M N O

D E F

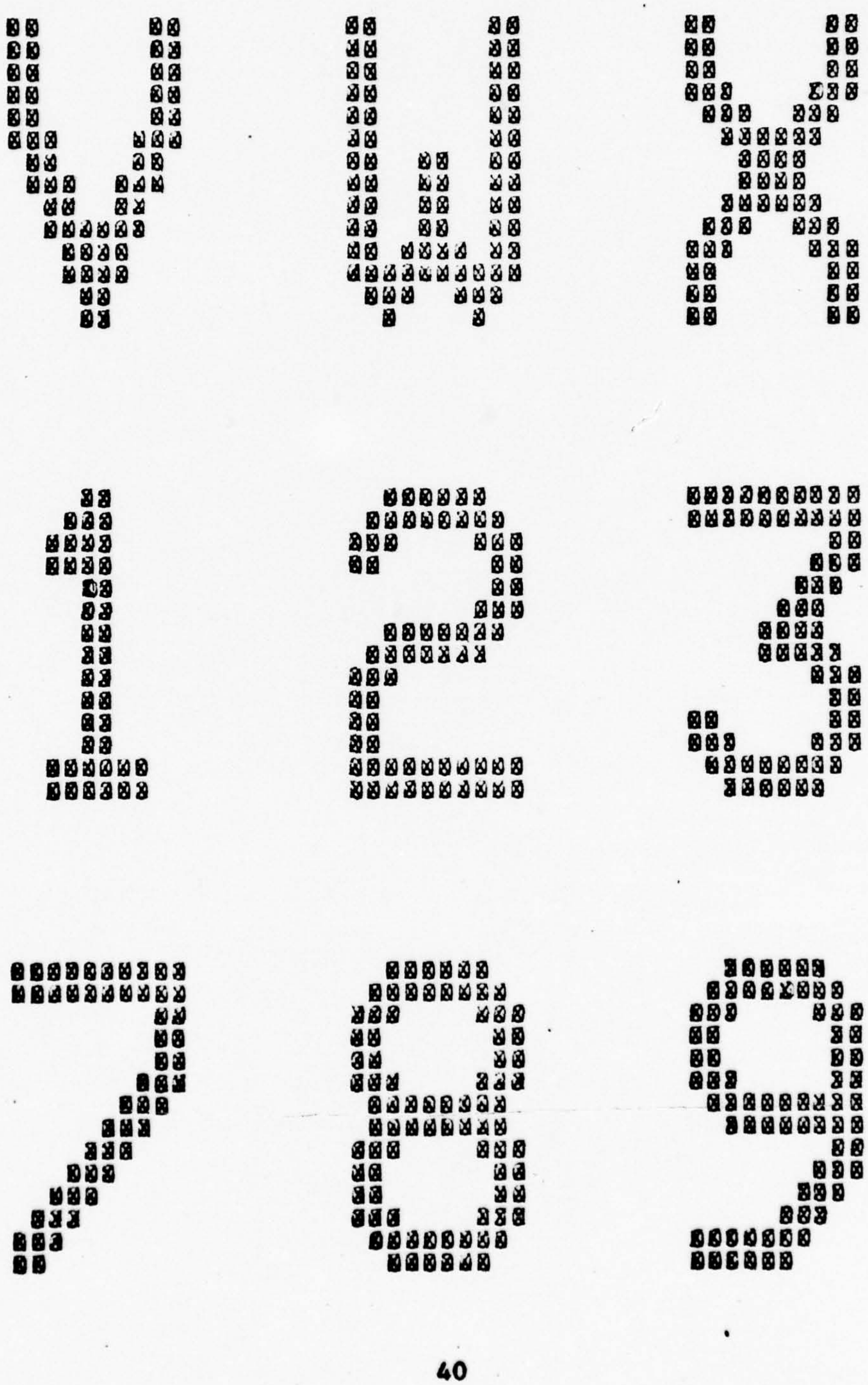
J K L

P Q R

S T U

Y Z 0

4 5 6


V W X
1 2 3
7 8 9

Appendix C

NAMEL Set

D E F

J K L

P Q R

S T U

Y Z 0

4 5 6

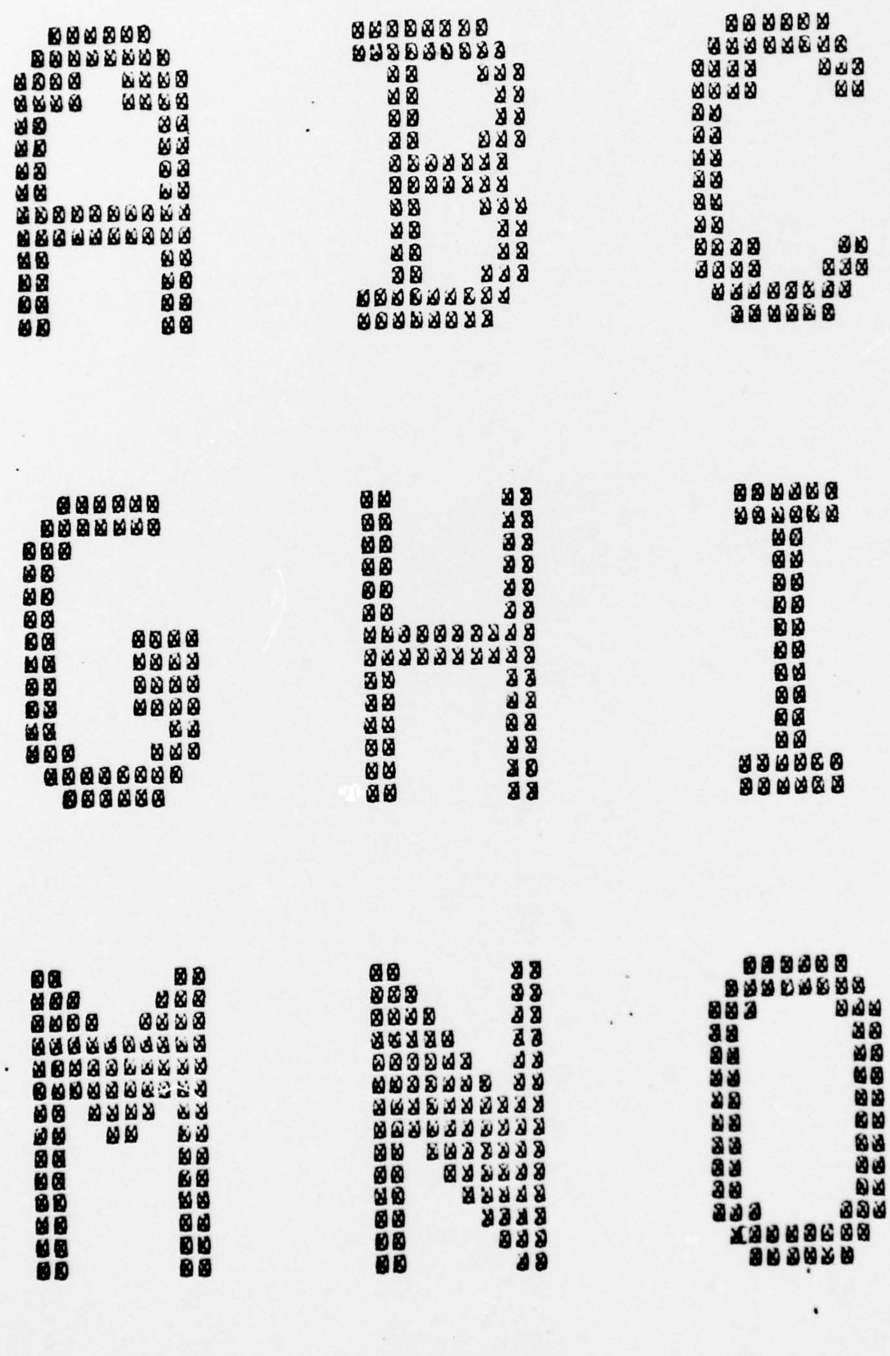
Y W X

1 2 3

7 8 9

Appendix D

Huddleston Set



D E F

J K L

P Q R

V W X

1 2 3

7 8 9

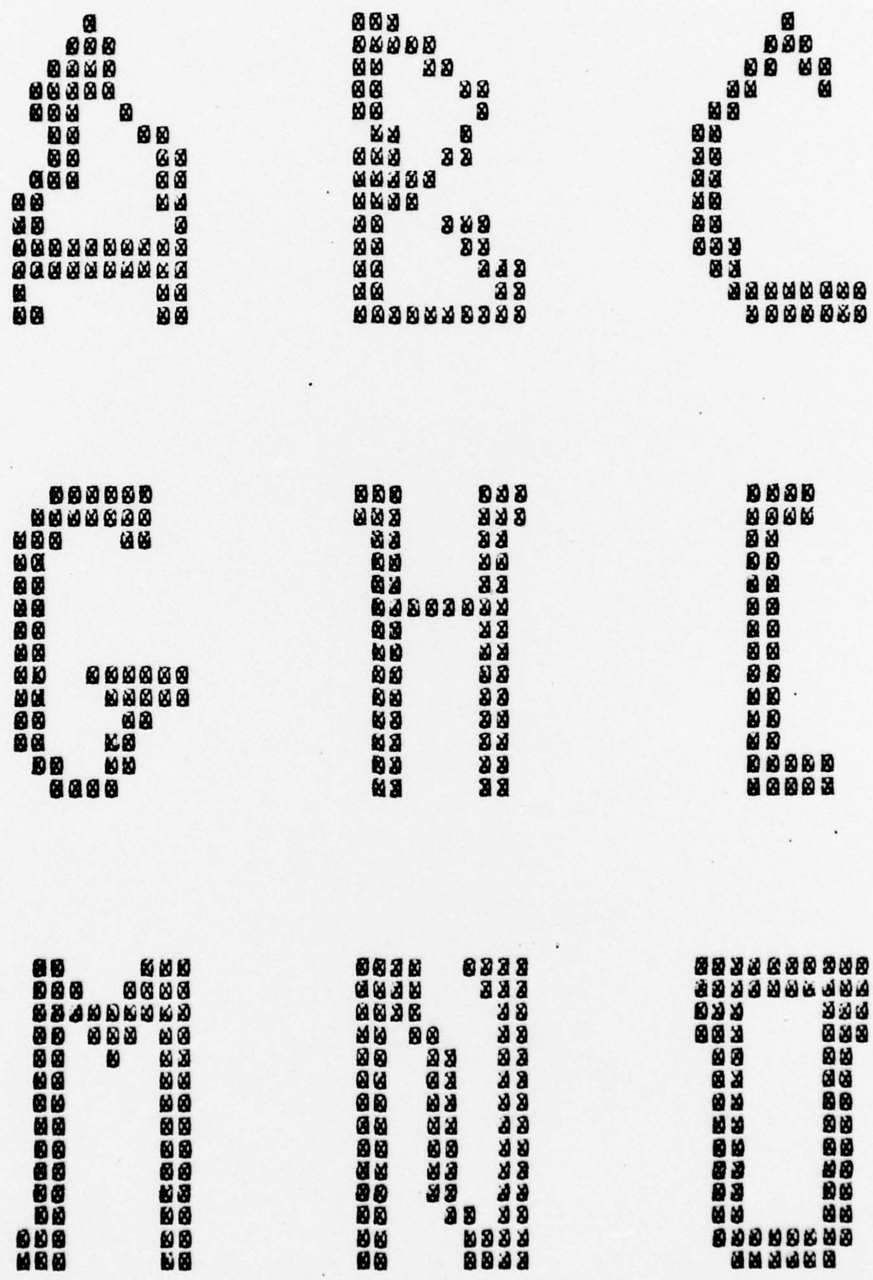
S T U

Y Z Ø

4 5 6

Appendix E

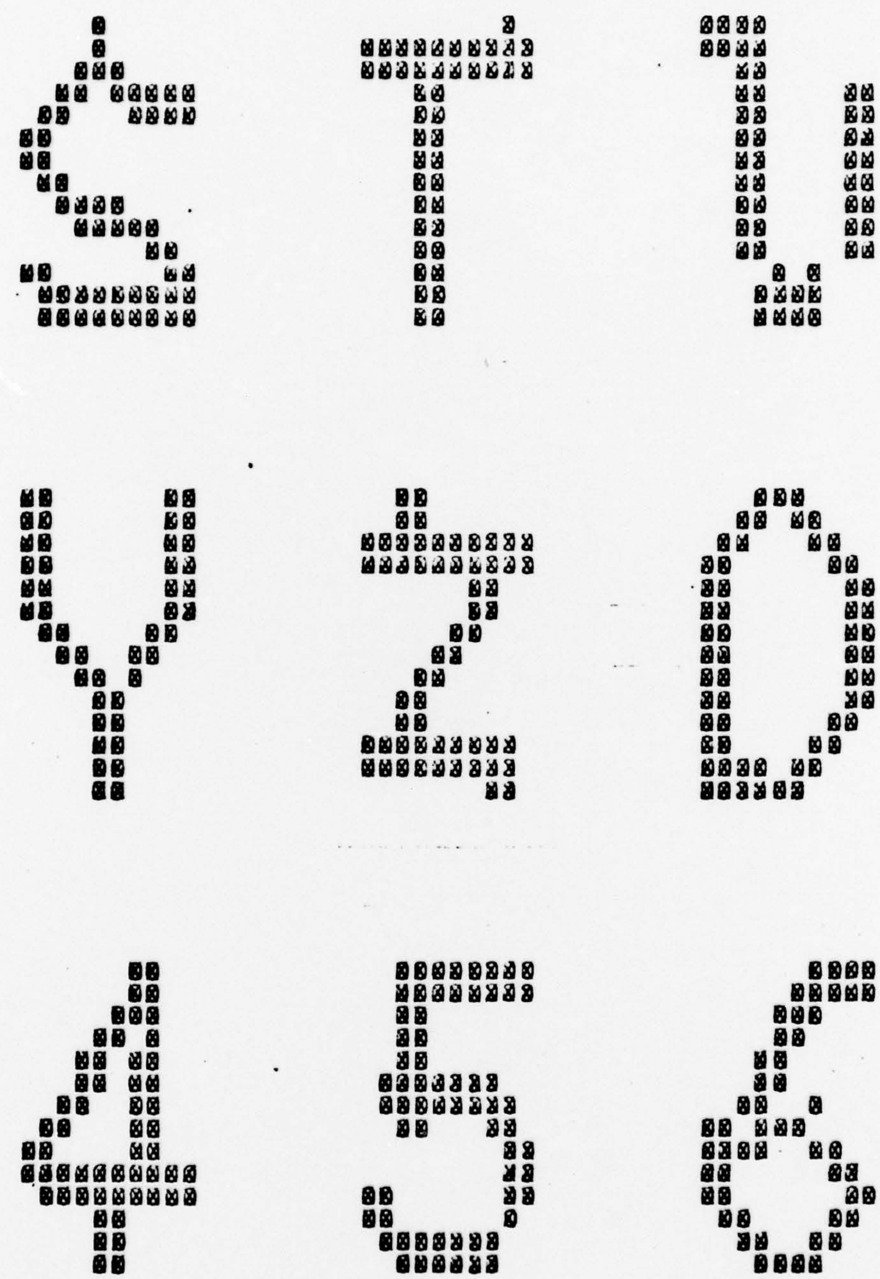
Experimental Set
Alphanumeric Symbols

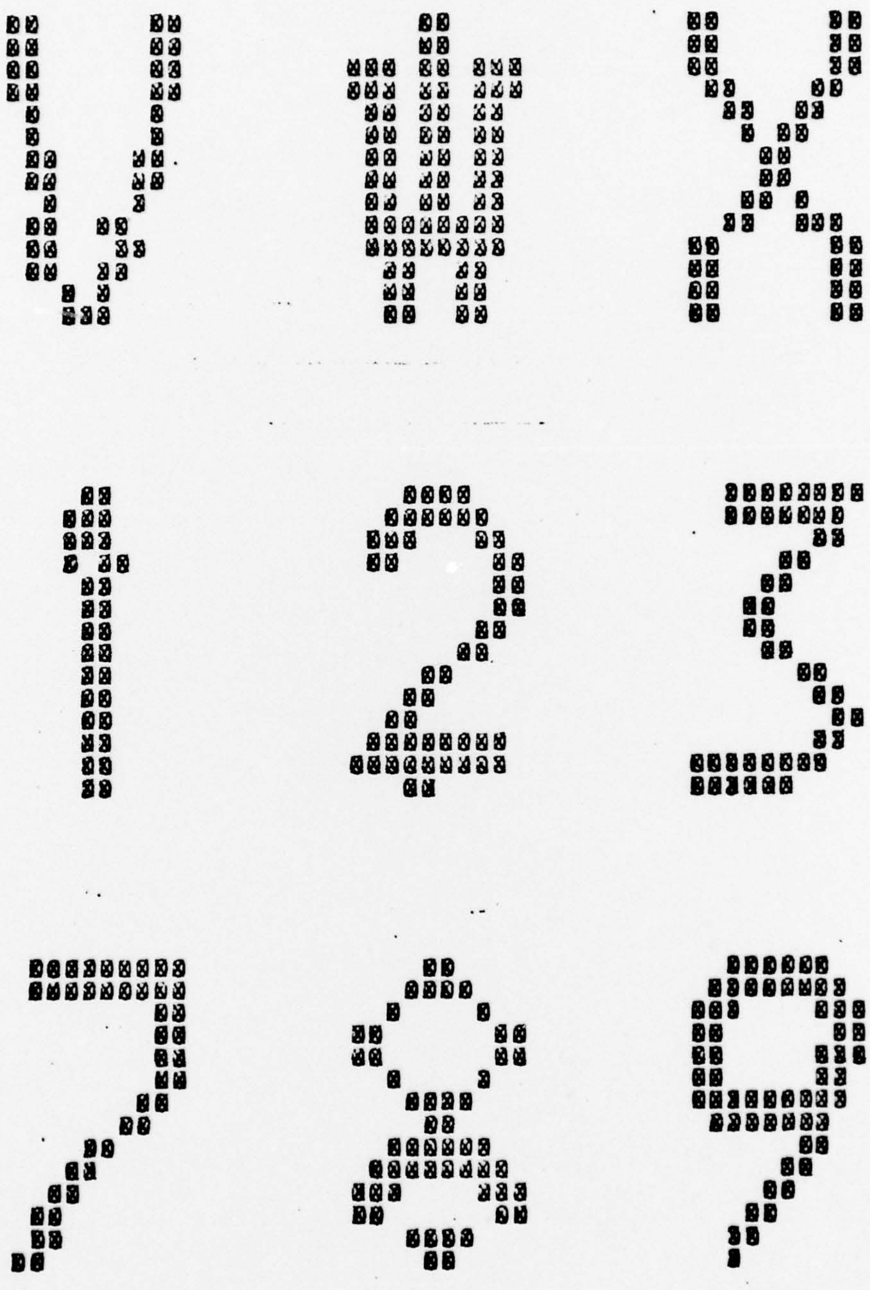


D E F

J K L

P Q R





VITA

Harvey D. Dahljelm was born on 12 February 1946 in Highland Park, Michigan. He graduated from high school in East Lansing, Michigan and attended Michigan State University from which he recieved the degree of Bachelor of Science, Electrical Engineering, in June 1968. He recieved a commission in the USAF and attended Navigator Training School at Mather AFB, California. After recieving his wings in March 1970, he completed Electronic Warfare School and was assigned to the 121st Reconnaissance Squadron at Korat RTAB, Thailand. In 1971, he was diverted to the 16th Special Operations Squadron at Ubon RTAB, Thailand and he served as an AC-130 Electronic Warfare/Fire Control Officer. After return from Southeast-Asia in January 1972, he served as a B-52 Instructor Electronic Warfare Officer in the 644th Heavy Bombardment Squadron at K. I. Sawyer AFB, Michigan. He was assigned temporary duty at Marham RAF, England; Anderson AFB, Guam and U-Tapao RTAB, Thailand. In 1975, he entered the Air Force Institute of Technology, School of Engineering, Graduate Electrical Engineering program at Wright-Patterson AFB, Ohio.

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Spatial Filtering
Symbol Legibility

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Legibility is of fundamental importance in pattern recognition. Legibility of five sets was predicted by using maximum-minimum Euclidean distance of separation in a feature space spanned by truncated, two-dimensional, discrete Fourier spatial frequency components of alphanumeric symbols. ASCII, Huddleston, NAMEL, Lincoln/Mitre and a combination set were psychophysically tested and ranked according to the least number of human errors. Test results confirmed legibility prediction: combination, Lincoln/Mitre, Huddleston, NAMEL and ASCII. For a symbol pair, as distance of separation increased the number of errors decreased and the majority of the errors occurred within the five nearest symbols to the symbol.

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